Methodology for monitoring rolling element bearing machines

Bently Nevada's methodology for monitoring rolling element bearing machines is based on both the principles of rotating machinery behavior and the particular vibration characteristics of rolling element bearings. It combines traditional strategies for detecting rotor-related problems, such as unbalance and misalignment, with special techniques for identifying rolling element bearing defects. This methodology depends upon a monitoring system with two qualities. It must provide diagnostic data for detecting and preventing common rotor and bearing-related problems, and it must give adequate warning of problems, to avert machine failure. The system must be sophisticated enough to discriminate among bearing faults, and give warning only when the damage could be seen with the unaided eye. A monitoring system that meets these criteria will detect most problems before serious damage results, and give you confidence in the condition of important rolling element bearing machines.

The following article is taken from a Bently Nevada Applications Note that was published nine years ago. The method advocated then on how to properly monitor rolling element bearing machines has been verified to work through extensive field experience. The most appropriate machinery management system for monitoring rolling element bearing machines is Trendmaster® 2000 for Windows®, Bently Nevada's scanning, online monitoring system for general-purpose machinery. It immediately informs operators of machine problems, so they can take action to reduce machine stress and maintain production. The system gives maintenance personnel early warning of failure, so they can obtain spare parts and schedule corrective actions.

The difference between rolling element and fluid-film bearings

Machines with fluid film bearings and machines with rolling element bearings each require different monitoring and diagnostic techniques, because the bearings are fundamentally different. The thin fluid film that supports the shaft, in a fluid film bearing, permits shaft movement relative to the bearing. A proximity transducer is designed to measure such movement, and is, therefore, the best transducer for fluid film bearings.

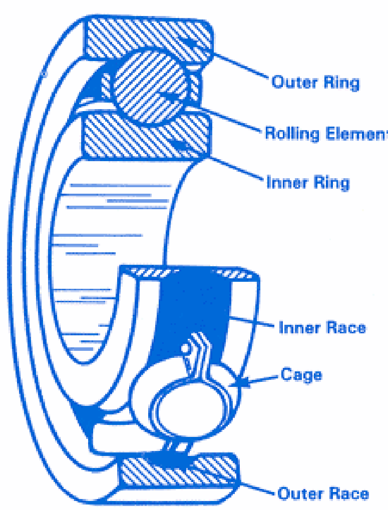


Figure 1
Rolling element bearing.

A rolling element bearing, however, has extremely small clearances which allow very little shaft motion relative to the bearing (Figure 1). Forces from the shaft, which would move a shaft supported by fluid-film bearings, are instead transferred through the bearing to the bearing housing. Therefore, a casing measurement is normally acceptable for machines with rolling element bearings. However, the most accurate system for measuring rolling element bearing vibration is the REBAM® System, available from Bently Nevada. It measures vibration directly on the bearing outer ring. This direct measurement greatly enhances bearing vibration data, and in some cases, it is the only measurement that can provide adequate vibration information.

Rolling element and fluid film bearings also produce very different vibration characteristics. The vibration signal from a rolling element bearing contains several components that are related to the bearing geometry, the number of rolling elements, and the bearing's rotative speed. No comparable vibration components are generated by a fluid film bearing.

Rolling element bearing geometry and vibration

The frequency components generated by a rolling element bearing can be calculated, although it is usually not essential for machinery management, for two reasons. First, bearing flaws, and associated frequency components change, as a flaw on one element causes flaws on other elements. Second, these calculated

frequencies are of little help in anticipating and scheduling repairs. A rolling element bearing is replaced as a unit, so it is only necessary to know the overall extent of bearing damage. Despite that, these frequencies can sometimes help isolate the root cause of premature bearing failures, and help target long-term, corrective action.

Rolling element bearings are of several types: ball, cylindrical, spherical, tapered, and needle. Each consists of an inner and outer race, separated by rolling elements, which are usually held in a cage (Figure 1). Mechanical flaws can develop on any of these components. As the bearing rotates, flaws generate frequency components that are related to the bearing's basic geometry.

In most applications, the bearing's outer race is fixed and does not rotate. There are exceptions; in some installations, either the inner or outer race, or both races, rotate. Figure 3 summarizes the main frequency components generated by a rolling element bearing with a fixed outer race. These frequencies may, and often do, include sum and difference frequencies. Often, they are modulated by the equipment's rotative speed.

Categorizing bearing frequency components

The frequency components generated by a rolling element bearing as it rotates are due the motions of its components (Figure 2). These vibrational components are generated even in a new bearing, although the amplitudes are small. The most important are:

- Inner and outer roller pass frequencies are caused by balls (rolling elements) as they pass over a flaw on the inner or outer race. Bently Nevada uses the Outer Race Element Pass frequency (EPx) to define relative frequency ranges that help categorize bearing faults. The inner and outer roller pass frequencies can be calculated directly from the bearing geometry, if there is no slippage or dimensional change with load.

- Roller spin frequencies, caused by rolling element flaws or a defect in the cage. A flaw in a roller can generate frequencies at twice the roller spin frequency, by hitting both the inner and outer races with each roller rotation.

- The cage frequency, which is the frequency at which the rollers revolve as a set. It is less than one-half rotor speed on bearings with a stationary outer ring.

Any combination of flaws can generate, or be modulated by, the cage frequency.

Bently Nevada's methodology makes it easier to determine the source of vibration, by separating rolling element bearing vibration into three frequency regions:

- ***Rotor Vibration Region***

Rotor-related vibrations normally occur in the range of 1/4 to 3 times shaft rotative speed (1/4X to 3X); this is the Rotor Vibration Region. Rotor vibration is best analyzed in displacement units. Most general-purpose equipment, with speeds from 1200 to 3600 rpm, generate rotor-related vibration signals between 5 and 180 Hz (300 cpm to 11 kcpm).

Many rolling element bearing failures are the direct result of a rotor-related malfunction (e.g., unbalance, misalignment, or fluid-induced instability). Rotor-related malfunctions contribute to bearing overload, and premature bearing failure. They must be corrected to ensure that bearings give the longest service possible. A diagnostic system must monitor this frequency range; otherwise, rotor-related malfunctions might remain undetected, and the machine's bearings will continue to fail prematurely.

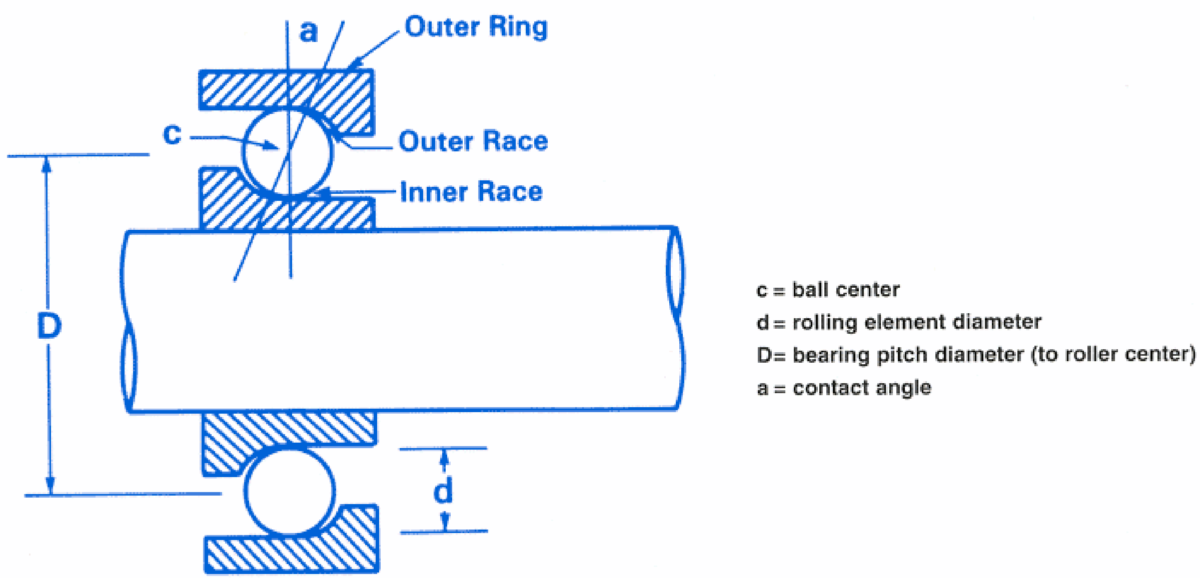
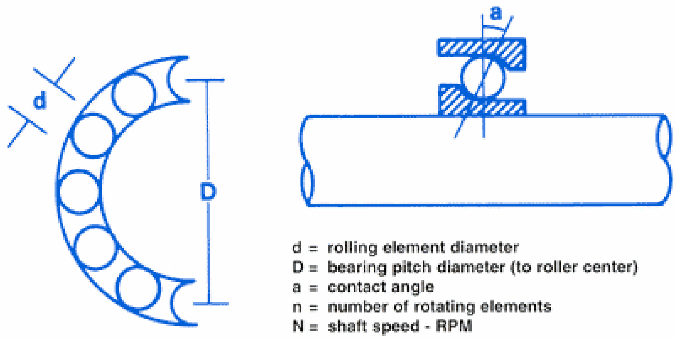


Figure 2
Basic rolling element bearing geometry (assuming no slippage or change in bearing geometry with load).



d = rolling element diameter
D = bearing pitch diameter (to roller center)
a = contact angle
n = number of rotating elements
N = shaft speed - RPM

Frequency Component (CPM) *

Cage Frequency . . . $(N/2)\,[1-(d/D)(\cos a)]$

Roller Spin . . . . $(N/2)\,(D/d)\,\{1-[(d/D)\cos a]^2\}$

2x Roller Spin . . . . . $N\,(D/d)\,\{1-[(d/D)\cos a]^2\}$

Outer Race Defect . $(N/2)\,(n)\,[1-(d/D)\,(\cos a)]$

Inner Race Defect . . $(N/2)\,(n)\,[1+(d/D)\,(\cos a)]$

*Note that the flaws on one element are rapidly transmitted to the other elements.

Figure 3
Frequencies when outer race is fixed (the frequencies are exact if no slippage or load changes occur).

The Rotor Vibration Region is not exclusive to rotor-related vibration components. Bearing-related frequencies can also occur in this region. A damaged cage can produce vibrational components below 1/2 shaft rotative speed (if the bearing has a stationary outer ring). Also, studies of the REBAM® System show its signal can contain frequency components in the Rotor Vibration Region, that are caused by spalling on a bearing's inner race.

• *Prime Spike Region*

The Prime Spike Region is defined by Bently Nevada as the frequency range which includes components generated by rolling elements as they traverse either an inner or outer race flaw. These frequencies are related to the bearing's geometry and speed, and are normally 1 to 7 times the Outer Race Element Passage frequency (1 to 7 EPx). Vibrations in the Prime Spike Region can be measured effectively as acceleration, velocity or displacement.

• *High Frequency (Spike Energy) Region*

The High Frequency (Spike Energy) Region contains frequencies from 5 kHz to approximately 25 kHz (8 EPx and higher), and is measured with accelerometers. High Frequency Region measurements are not a primary indicator of bearing failure; if used for that purpose, it should be only as a supplement to Rotor Vibration and Prime Spike Region measurements. High Frequency Region measurements have two appropriate uses:

• High frequency signals occasionally indicate a bearing problem at the prefailure stage. Care must be exercised, however, because bearing flaws "self-peen," which causes readings in this high frequency region to decrease as bearing flaws progress. Self-peen means the bearing works the surfaces of the races and rolling elements, removing the sheer edges, which reduces the impacts and causes the high frequency vibration to diminish.

• High frequency signals can help detect certain other machine malfunctions, such as cavitation, rubs, steam or gas leaks, valve problems, blade passage or gear mesh problems.

High frequency vibration energy attenuates very rapidly with distance. Therefore, a transducer will not detect high frequency vibration unless it is near its source. This has two implications for machinery diagnostics. First, a fault that generates high frequency vibration may go undetected if a transducer is not located near it. Second, if a transducer does detect high frequency vibration, then the fault that caused it must be near the transducer.

These three frequency bands, defined by Bently Nevada, help machinery specialists to quickly categorize rolling element bearing machine problems. Field studies indicate that approximately 90% of all bearing failures are related to either an inner or outer race flaw. Bently Nevada, and many of our customers, have found that most of this information is contained in the Prime Spike region (1 to 7 EPx).

The bearing failures not related to inner or outer race flaws are mostly due to flaws on either the cage or the rolling elements. Cage flaws produce vibration components in the Rotor Vibration Region.

Rotor-related malfunctions shorten the life of rolling element bearings, and are evident in the Rotor Vibration Region. The High Frequency Region may give an early indication of bearing failure, as well as identify other problems unrelated to bearing faults.

Causes of failure in rolling element bearings

A rolling element bearing has a finite life and will fail due to fatigue and friction, even if operated under ideal design conditions. Rolling element bearing manufacturers realize this, and have developed design life limits (L_{10}/B_{10}) to indicate the bearing's estimated service lifespan, assuming it is installed and operated within design limits. L_{10}/B_{10} is defined as the rating life of a group of apparently identical rolling element bearings, operating under identical loads and speeds, with a 90% reliability before the first evidence of fatigue develops. Unfortunately, most "real world" installations are not ideal, so most bearings fail well before their rated design life. Most premature bearing failures can be

attributed to one or more of the following causes:

- Excessive loading. The excessive load can be steady state, because of misalignment or static radial load, or dynamic, because of unbalance or another problem.
- Improper lubrication - insufficient or excessive.
- External contamination
- Improper installation
- Incorrect sizing, for example, a bearing of the wrong design.
- Exposure to vibration while not rotating (false brinelling).
- Passage of electric current through the bearing.

A successful predictive maintenance program will identify both rolling element bearing failures and the failures' root causes. Maintenance is not complete until the root cause of a failure has been corrected, so it will not recur.

A rolling element bearing progresses through three failure stages, each of which exhibits vibration characteristics that require specific diagnostic and monitoring techniques.

The stages are:

1. Prefailure
2. Failure
3. Near catastrophic or catastrophic failure

Prefailure Stage

At the prefailure stage, the bearing is in the earliest stages of failure. It develops hairline cracks or microscopic spalls that are not normally visible to the human eye, since most of the early damage occurs below the surface of the race. During this stage, high frequency (greater than 7 EPx) vibration may increase. However, temperature and Prime Spike Region vibration measurements will be normal. The bearing usually has a significant amount of safe operating life left, so it is not economical to replace it at this time.

Failure Stage

This is the stage at which the bearing develops flaws that are visible to the human eye. The bearing usually produces audible sound, and its temperature rises. Vibration amplitudes in the bearing-related, Prime Spike Region reach easily detectable levels. At this stage, the bearing should be replaced. If not, it must be monitored more frequently, to protect the machine from serious damage. This is the most economical time at which to replace the bearing. If the bearing is not replaced now, its condition will eventually deteriorate, to the near catastrophic or catastrophic stage.

Near catastrophic or catastrophic stage

When the bearing enters this stage, rapid failure is imminent. Audible noise increases significantly, and the bearing's temperature increases until it overheats.

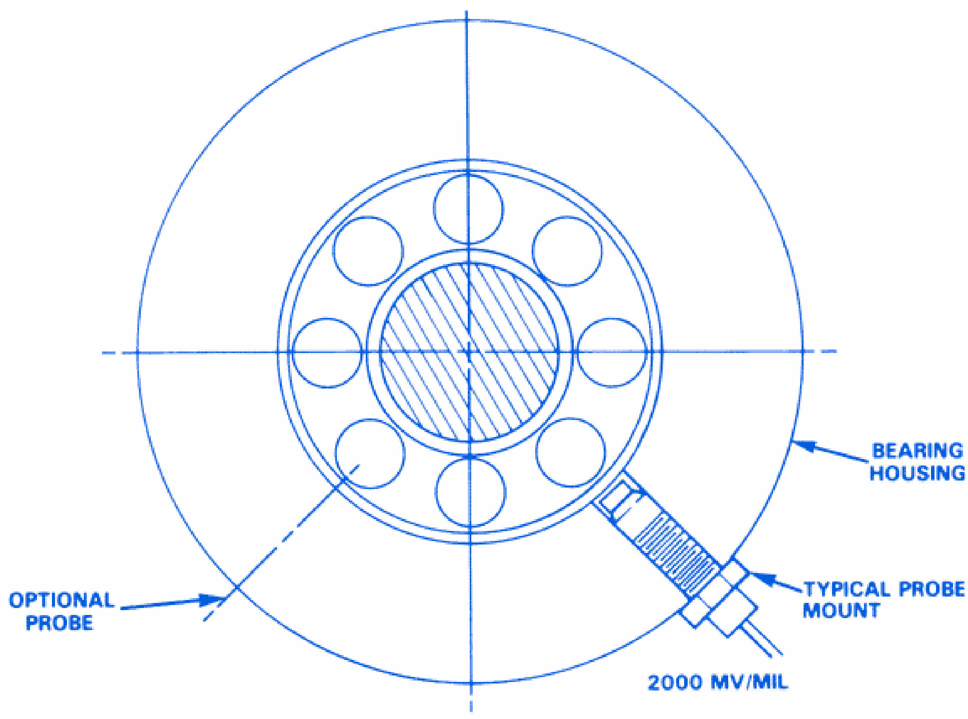


Figure 4
Typical REBAM (Rolling Element Bearing Activity Monitor) probe mount.

Rapid wear increases the bearing's clearance, which allows significant shaft motion relative to the bearing. Since a rolling element bearing is designed to restrict shaft motion, increased bearing clearance is very dangerous, because it can cause a rub within the machine. Bearing-related, Prime Spike Region vibration increases significantly. However, High Frequency Region vibration often decreases during this stage, because of bearing flaw "self-peening." It may appear to indicate that the bearing is in an earlier stage of failure. This data is unreliable, and should be viewed with caution. The "self-peening" phenomena is especially evident in low speed high radial load machines.

Transducers for rolling element bearing machines

Two types of transducers are appropriate for measuring vibration on rolling element bearing machines. One is the REBAM® System, which directly measures bearing motion. REBAM is an acronym for **R**olling **E**lement **B**earing **A**ctivity **M**onitor. The other type of transducers are casing-mounted transducers, which include velocity transducers and accelerometers.

REBAM® System

The REBAM transducer is a high-gain, low-noise eddy current proximity transducer. It is installed in the bearing housing, where it observes the bearing outer ring (Figure 4), which contains the outer race. The REBAM transducer measures the very small displacement of the outer ring as rolling elements pass. The operating frequency range for the REBAM transducer system is from 0 Hz (dc) to 10 kHz (0 to 600 kcpm). The REBAM transducer makes a very direct and very sensitive measurement of vibration in rolling element bearings. It has a much higher signal-to-noise ratio than casing-mounted acceleration or velocity transducers.

The REBAM monitor uses electronic filters to separate the REBAM transducer signal into Rotor Vibration and Prime Spike Regions. Typical Prime Spike amplitudes are 10 to 50 microinches (0.25 to 1.3 micrometres) for a good bearing, and 2 to 5 times higher for a damaged bearing. However, signal amplitude is highly dependent upon the actual load on the elements as they pass the transducer. Therefore, common practice is to take baseline readings on a healthy bearing, and then set the monitor's Alert and Danger alarm levels at 1.5 and 2 times the baseline level. Field and lab tests confirm that such alarm levels provide adequate failure protection.

Case-mounted transducers

Rolling element bearing condition can also be indicated through casing vibration measurements. These measurements include overall velocity Prime Spike velocity, and high frequency acceleration. Bently Nevada can provide accelerometers and velocity transducer-based systems to monitor rolling element bearing condition. Overall casing velocity or acceleration measurement indicates the general mechanical condition of rolling element bearing machinery.

A velocity transducer-based system has a frequency range of 10 Hz to 1 kHz (600 cpm to 60 kcpm). Depending on the machine speed, the velocity system's frequency range is likely to span the Rotor Vibration Region and the lower end of the Prime Spike Region.

An accelerometer-based system has a frequency range of 10 Hz to 20 kHz (600 cpm to 1,200 kcpm). This range spans the Rotor Vibration, Prime Spike, and High Frequency Regions. However, as mentioned earlier, high frequency measurements are appropriate only as a early indicator of developing problems.

When using casing measurement systems, two key factors should be considered. The first is signal amplitude versus transmission distance, and the second is noise susceptibility.

The farther a transducer is located from the source of vibration, the more its signal is attenuated. Most rolling element bearing machines have joints between machine parts, which further attenuates the vibration signal. The best measurements are made very near the vibration source. Therefore, a casing-mounted transducer should be located within 25 to 50 mm (1 to 2 inches) of a rolling element bearing.

Signal-to-noise ratio is defined as the ratio of the amplitude of a desired signal at any point to the amplitude of noise signals at that same point. Transducer systems vary in their signal-to-noise ratios, so pay careful attention to their specifications.

It is important to note that REBAM is the only useful approach for "low" speed, high radial load rolling element bearing machines. Velocity and acceleration probes will not measure rotor-related problems for low speed machines, due to their poor signal-to-noise ratio.

Summary

Bently Nevada's methodology for rolling element bearing machines supports both immediate and long-range machinery management goals. Its most important function is to identify problems early, so plants can avoid machine failure and downtime. Overall vibration measurements on the rotor vibration and Prime Spike Regions usually provide sufficient information for this goal.

Long-term, it improves machine performance by establishing the fundamental cause of failures, so similar failures can be avoided in the future. Fundamental cause analysis requires a system that can isolate problems through their vibration characteristics. Bently Nevada's methodology simplifies this process by distinguishing problems as either rotor-related (unbalance, misalignment, fluid-induced instability, etc.), or bearing-related, based on vibration characteristics. ■

References

1. Hansen, J. Steven and Harker, Roger G., "A New Method for Rolling Element Bearing Monitoring in the Petrochemical Industry," Presented at the Vibration Institute Seminar, New Orleans, Louisiana, June 1984.
2. Foiles, Bill, "Rolling Element Bearing Frequencies," Edited by Bently Nevada Corporation.